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ELECTRO-MAGNETS:

THE
DETERMINATION
OF THE
ELEMENTS OF THEIR CONSTRUCTION.

By TH. Du MONCEL.

(*Translated from the Second Edition.*)

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TRANSLATOR'S PREFACE.

The timely appearance of this practical essay of Du Moncel will doubtless be regarded with much satisfaction by more than one class of scientific readers. Besides the large class of scientific students who feel a general interest in obtaining a more definite knowledge of topics so obscurely treated in current literature, there is a large and increasing number of amateur experimenters, as well as working artizans, who can gain much desired information from this little book.

The fame of the author is so securely and widely established, that nothing need here be said regarding the weight of the authority that presents the practical rules herein contained as safe guides for the constructor.

The essay appears here substantially as published in Vol. 28 of VAN NOSTRAND'S MAGAZINE.

TABLES FOR CONVERTING METRIC INTO ENGLISH MEASURES.

Long Meters.

	Meters.	Inches.	Feet.	Yards.
Millimetre	.001	.03937	.00328	.00109
Centimetre	.01	.3937	.0328	.0109
Decimetre	.1	3.937	.328	.1093
Metre	1	39.37079	3.2809	1.09363

Weights.

	Grammes.	Avoirdupois ounces.	Avoirdupois lbs.
Milligramme	.001	—	—
Centigramme	.01	—	—
Decigramme	.1	—	—
Gramme	1	.035	.0022
Kilogramme	1,000	35.2739	2.2046

Linear Measures.

		Metres.	Reciprocals.
Inch	=	.02539954	39.37079
Foot	=	.3047945	3.280899
Yard	=	.91438348	1.093633

ERRATA.

Page 10, bottom line, add $\pi=3.14$=ratio of the circumference of a circle to its diameter.
Page 25, line 9, for "giving" read "given."
Page 26, line 11, for "dimensions" read "length."
Page 29, line 19, erase "that."
Page 32, line 20, for "of" read "for."
Page 121, line 7, for "they" read "it is."

ABBREVIATIONS.

km. = kilometres.
m. = metres.
cm. = centimetres.
mm. = millimetres.
kg. = kilograms.
gr. = grams.

CONTENTS.

CHAPTER I.—Formulas for Electro-Magnets.

" II.—Conditions of Maximum Effect on a Simple Circuit.

" III.—Conditions of Maximum Effect on Derived Circuits.

" IV.—Application of these Laws to the Construction of Electro-Magnets.

" V.—Numerical Examples.

" VI.—Experimental Verification of the Laws.

" VII.—Effects of Saturation of Electro-Magnets.

" VIII.—Conditions of Construction.

" IX.—Conditions of Arranging the Cells of a Battery.

" X.—Tables of Dimensions and Resistances of Wire, etc.

The Construction of Electro-Magnets.

THE complaint is general and not without reason, that the subject of electro-magnetism is so obscurely treated by scientists, and the conclusions reached by them are of so little practical value, that the inventor or constructor can derive no profit from them. It is certain that the mathematical physicists regard such problems of too high an order to permit themselves to be diverted by a consideration of the practical applications, and it may be said furthermore that the theories of magnetism are not as yet easily expressed in mathematical symbols, and many of the so-called laws are still matters of controversy with the more conservative.

For ourselves, having made many experiments, we are less skeptical, and although we have not been able to verify rigorously the laws as propounded by

Lenz, Jacobi, Dub and Müller, we have obtained results so nearly approaching to verification, that we admit them as guides in the construction of electro-magnets. Ohm's Law relating to electric currents is on the same footing, for it is difficult to take cognizance in the formula of a multitude of secondary reactions which interfere more or less with the calculated results. But these laws are faithful guides which enable us to place ourselves in conditions favorable for success, and that is the essential point.

In order to render such a scientific fact practically useful, it is necessary to be unencumbered with the hypotheses of the higher physics and those terms which but few electricians understand, and to start with experiments made under ordinary conditions. It is certain that if, to appreciate a magnetic force it is necessary to begin with the oscillations of a magnetic needle, or with the currents induced by such force, to arrive at the necessary formulas, the practical constructor can say that though such formulas afford no mental conception of magnetic force, he knows that they relate to a definite weight attracted or supported, and that the real object being to attain the greatest force under given conditions, other considerations are of little importance. It is under such conditions that it is necessary to approach the problem in order to arrive at practical results.

Now I have always admitted that the known laws of electro-magnetism were sufficient for the purposes of the artisan, and upon this idea I have based the different papers published on the best conditions of construction of electro-magnets. Wishing to be sure of my deductions, I have made many experiments in order to verify my formulas, and it was only after the most careful experimental research the writer established the formulas given.

I.—Formulas of Electro-Magnetism.

In order to establish my formulas, I start from the elements entering into the construction of the electro-magnet; knowing the dimensions of the core, the size of the wire of the helix, its length; the number of spiral turns in this helix, and its thickness.

Let a = the thickness of the helix.

b = the total length of the two spools or the two branches of the electro-magnet.

c = the inside diameter of the helix, which is presumably the same as the core or magnet.

g = the diameter of the wire of the helix, including its insulating envelope.

A = the attractive force of the magnetic system.

E = the electromotive force of the pile employed.

F = the force of the electro-magnet or its *magnetic moment.*

H = the length of the helix.

I = the intensity of the current in the circuit.

t = the number of turns in the spiral.

R = the resistance of the circuit, including the battery.

It is easily seen that we can represent the number of spiral turns of each layer by $\frac{b}{g}$, and as there are as many layers of wire as g is contained times in the thickness a, we shall have for the total number of turns t

$$(1) \qquad t=\frac{b}{g}\times\frac{a}{g}=\frac{ab}{g^2}.$$

The length of a single turn of the wire in the first or inner layer is $2\pi\frac{c+g}{2}$, and for the outermost $2\pi\frac{c+2a-g}{2}$, and consequently the total length of these layers is $\frac{b}{g}\cdot 2\pi\frac{c+g}{2}$ and $\frac{b}{g}2\pi\frac{c+2a-g}{2}$.

The intermediate layers form with these two an arithmetical progression of which the above expressions are the extreme terms, and the number of terms is $\frac{a}{g}$. The sum of this series, or the total length of the wire, will be given by the formula:

$$(2) \qquad H=\frac{b}{g}\,\frac{2\pi(c+g+c+2a-g)}{4}\,\frac{a}{g}$$

$$=\frac{\pi ba(a+c)}{g^2}.$$

The values of t and H are thus obtained in terms of the different elements entering into the construction of an electro-magnet.

These formulas are useful, as they enable us to determine the length and number of turns of the wire of a helix, from the dimensions of the wire, and the thickness and length of the helix.

An expression for the electro-magnetic force is obtained by starting from the laws of Jacobi, Dub and Müller, which express the value of the force F of an electro-magnet or its magnetic moment, in terms of the intensity I of the electric current and the number of turns of the helix; the formula being

$$F=\frac{Et}{R+H};$$

and the value of the attractive force A by the square of this expression; or

$$A=\frac{E^2t^2}{(R+H)^2}.$$

By substituting for t and H in these formulas the values previously obtained, we get:

$$F=\frac{Eab}{Rg^2+\pi ba(a+c)}$$

and

$$A=\frac{E^2a^2b^2}{[Rg^2+\pi ba(a+c)]^2}.$$

The formulas enable us to determine different conditions of maximum effect according as we change the values of a, b, c and g. These conditions are dependent on, 1st, the resistance to be given to the helix; 2d, the ratio between the size of the helix and the magnetic core; and, 3d, the dimensions of the electro-magnet itself.

The different parts of the circuit are composed of different conductors, and it becomes necessary in determining the resistance to consider the wire of the helix, apart from its covering. As g represents the diameter of the covered wire, we may take $\frac{g}{f}$ for the diameter of the naked wire; f having a value of 1.6 for very fine wire, and 1.4 for the medium sizes.

Now in modifying the value of R in the formula so as to involve the above condition, the different conducting powers of the helix and the remainder of the circuit must be taken into account. If q be taken to represent the ratio of conductivity, we shall have for the modified value of R the expression $\frac{qRg^2}{f^2}$. The unit section of conductivity being

$$0\overset{\text{m}}{.}000016.$$

Now if the diameter $\frac{g}{f}$ of the wire of the helix is made to vary while the thickness of the helix remains constant, the length will vary also, so that the resistance of the helix will vary inversely as g^4.

As the value of H in the preceding formulas represents the resistance of the helix, the denominators of the values of F and A become:

$$\frac{q\mathrm{R}g^4+\pi ba(a+c)f^2}{f^2g^4} \text{ and } \left(\frac{q\mathrm{R}g^4+\pi ba(a+c)f^2}{f^2g^4}\right)^2$$

and the values themselves:

$$(3)\quad \begin{cases} \mathrm{F}=\dfrac{f^2g^2\mathrm{E}ab}{q\mathrm{R}g^4+f^2\pi ba(a+c)}, \text{ and} \\ \mathrm{A}=\dfrac{f^4g^4\mathrm{E}^2a^2b^2}{[q\mathrm{R}g^4+f^2\pi ba(a+c)]^2}. \end{cases}$$

II.—CONDITIONS OF MAXIMUM EFFECT OF ELECTRO-MAGNETS ON A SIMPLE CIRCUIT.

1st. Conditions as determined by the resistance of the helix.

The values of A and F as given above may be discussed from different points of view. The conditions of maximum effect, for instance, may be required for an electro-magnet of *fixed dimensions*, and it is desired to adapt its resistance to that of a given resistance R of the exterior circuit; or it may be required to adjust the resistance of the helix to that of the external circuit without being restricted in the dimensions of the helix. In the first case the variable quantity is the diameter g of the helix wire, and in the latter it is the thickness a of the helix itself.

When we consider that in the preceding formulas the diameter of the helix wire is not g, but $\frac{g}{f}$, in which f is a constant, we see that the calculation is not as simple as it appears at first sight, and for this reason, those who first employed these formulas neglected the value of f and employed g to represent the true diameter of the conducting wire. In taking into account the value of f, we shall not be able always to consider it constant while g is variable, and it is evident that on some occasions it will be necessary to regard this fact. But assuming only the more simple conditions of working, we easily determine from the preceding formulas that the conditions of maximum effect correspond to the equation

$$\frac{q\mathrm{R}g^2}{f^2} = \frac{\pi ba(a+c)}{g^2};$$

that is to say, $R=H$; which signfies that for electro-magnets of the same dimensions, having spools or helices of the same diameter, *that size of wire for the helix is most effective which renders the resistance of the helix equal to that of the exterior circuit.*

If we take the thickness of the covering of the wire into consideration, the formula proves that the most effective helix *is that whose resistance is to the resistance of the exterior circuit, as the diameter of the naked wire is to the diameter of the covered wire.*

If the thickness a of the helix be made to vary, and suppose the action of the spirals to remain the same (an admissible hypothesis under ordinary conditions when we take into account the difference of resistance arising from their greater distance from the soft iron core), the conditions of maximum effect as exhibited in the formula properly modified indicate that R should be equal to $\frac{\pi b a^2}{g^2}$. That is to say, equal to the length H of the wire of the helix divided by the ratio $\frac{a+c}{a}$, or what amounts to the same thing,

$$H=R\left(1+\frac{c}{a}\right).$$

Translated into ordinary language, this deduction signifies that, among several electro magnetic helices wound with wire of the same size, but having a different number of spiral turns, that which affords the best results upon a circuit of given resistance, *is that helix whose resistance is to the resistance of the external circuit as the thickness of the helix plus the diameter of the core is to the thickness of the helix alone.*

As in applications of electro-magnetism we generally start with a soft iron core of fixed dimensions, and as the conditions of maximum effect, of which we will presently speak, require that the thickness of the helix should be equal to the diameter of the core, and as, on the other hand, the thickness of the insulating cover varies and is thus far undetermined, it is one of the first things to be considered in the solution of the problem of construction. But for an experimenter who desires to know what resistance a circuit should have in order to produce the best effect with a given electro-magnet, the conditions explained in the following section indicate that the resistance of the external circuit should be *less than half that of the electro-magnet*, if the thickness of the helix is equal to the diameter of the core, as it should be.

2d. Conditions of maximum effect depending on the ratio between the thickness of the helix and the diameter of the iron core.

A second very important point in construction of electro-magnets is the determination of the limit of thickness to be given to the spools of wire to insure the best results. It is understood in a general way that the force of electro-magnets augments with the diameter of the core, and the resistance of the helix increasing in consequence of this increase of diameter, it is evident that there must be a limit at which the advantages gained by increasing the size of the core are counterbalanced by the increase of resistance in the helix. This limit may be determined by calculation.

In equations (3) expressing the values of the magnetic moment and the attractive force, F and A, we will make the quantity *c* (the diameter of the soft iron core) to vary, and establish an algebraic relation between it and a, the thickness of the helix. This is easily done, since we can suppose the helix wound directly upon the core, and its interior diameter will then be$=c$; and we shall be able in placing the electro-magnet in a condition of maximum effect in relation to the resistance of the exterior circuit, to obtain an expression susceptible of a maximum value, and the ratio of R to H will also be one or the other of those values established in the previous sections.

In representing by λ the coefficient by which to multiply the length of the helix to place the total circuit in one or the other of the conditions of maximum, and supposing the thickness of the helix *a* and consequently the number of turns of the wire *t* invariable; the attractive force A and the magnetic moment F have for values, according to the law of Müller relative to the increase of force with the diameter of the iron core,

$$(4)\quad F=\frac{g^2E\sqrt{c}}{\lambda\pi ba(a+c)} \text{ and }$$

$$A=\frac{g^4E^2c}{[\lambda\pi ba(a+c)^2]^2}$$

The expressions become maximum values for a certain value of *c*, but the quantities R and H are supposed to vary at the same time in proportion as the helix is elongated by reason of the increase of the magnetic core.

If we take the derivative of the preceding expression in relation to *c* considered as a variable, and equate it to zero, we find that the maximum corresponds to the condition $a=c$. That is, the thickness of the helix equals the diameter of the soft iron magnet. Now this is just the conclusion demonstrated by the experiments of the writer, also the conclusion to be reached at the end of this essay.

The advantages of the laws stated above are readily seen, as they enable us to simplify the calculations in determining the relative dimensions of the parts in constructing electro-magnets. The formula for the length of the helix wire, for instance, becomes, under the conditions for maximum effect, $= \frac{2\pi bc^2}{g^2}$ and if we regard the length b of the electro-magnet as a function of its diameter c, making $b = mc$, the above expression becomes

$$(5) \qquad \frac{2\pi c^3 m}{g^2} \text{ or } \frac{75.4c^3}{g^2}$$

making $m=12$ for both branches of the magnet, a proportion which accords well with good practice.

In this formula only two quantities, c and g, are required to be known, and which may be determined by means of relations which will be given further on. On the other hand, we have for the value of the number of turns of the wire in the helix,

$$(6) \qquad \frac{12c^3}{g^2}.$$

When the electro-magnet satisfies the conditions of maximum effect, $R=H$, $a=c$, and $b=cm$; as g is indeterminate it is necessary that R should be made a function of g. This is accomplished by putting the value of H equal to the length of wire required for R; whence

$$\frac{2\pi c^3 m}{g^2}=\frac{qRg^2}{f^2}$$

from which we get

$$g^4=f^2\frac{c^3}{R}\cdot\ \frac{2\pi m}{q},$$

and as the last fraction is composed of known terms, this value reduces to *

---

* In this expression q represents the ratio of conductivity or of resistances between R and H, R being expressed in meters of telegraph wire. As this wire is iron, and the helix is copper, the ratio is about 6. On the other hand, the diameter of the telegraph wire is 4 millimeters, and its cross-section is $0.^{m}000016$; q therefore equals $\frac{6}{0.000016}=375000$, and $\frac{2\pi m}{q}=0.00020106$ as above.

the length of the core. As this requires an increased number of turns of the wire, it compensates under certain conditions for the smaller diameter of the core. The theoretic formulas indicate the limit only indirectly for the conditions of maximum deduced by the preceding formula, taking c as the variable, give $\frac{2\pi c^3 m}{g^2}=11\ \mathrm{R}$. That is to say, according to the hypothesis admitted, *we can increase the dimensions of the magnetic core until the resistance of the magnetizing helix is eleven times the resistance of the exterior circuit.*

Under these conditions we have

$$m=11\frac{\mathrm{R}g^2}{2\pi c^3},$$

and we see that m becomes eleven times the ratio of resistance of the the exterior circuit to that of the helix when the diameter of the magnetic core equals its length; for in this case this helix has for its expression $\frac{2\pi c^3}{g^2}$; now, as the ratio of the resistance R to that of the helix should be = 1 to satisfy the conditions of maximum effect previously found, we deduce, from the preceding formula, $m = 11$.

In the calculations published in *Recherches experimentales sur les maxima electro-magnetiques*, by the writer, these conclusions are demonstrated.*

---

* Suppose, for example, three electro-magnets in a circuit of 64 meters of telegraph wire, the magnets having diameters respectively of $0.^{m}008$, $o.^{m}007$ and $0.^{m}006$, with lengths eleven times their diameters.

The first of these, is furnished with a helix of No. 12 wire, $0.^{m}0006$ in diameter, would have a helix 99 meters in length and a resistance represented by 1056 meters. The second magnet would have a helix with 66 meters length of wire, and 704 meters of resistance. The third $41.^{m}36$ for length of helix, and a resistance of 441 meters.

The numbers of terms of spiral deduced from the formula $\frac{11c^2}{g^2}$ is 1955 for the first magnet, 1497 for the second, and 1100 for the third. The $\frac{3}{2}$ powers of the diameters being 0.000715, 0.000585 and 0.00046 respectively, we find for the forces of the magnets 0.247868, 0.252891 and 0.250307. The advantage here is plainly with the second magnet, whose resistance is 704 meters, or eleven times that of the exterior circuit. But this is no longer the case if R be made equal to $704.^{m}$. The forces then become 0.10037, 0.07524 and 0.04871, *and it is* clearly the larger magnet that has

As the helices are generally furnished with a disk or spool-end, and the core projects slightly, and as at the lower or connected end a little space is needed for the connections, the coefficient 11 should be slightly increased. Experience indicates that it should be raised to 12.

III.—CONDITIONS OF MAXIMUM ON DERIVED CIRCUITS.

The deductions made in the preceding chapter suppose a permanent current established; that there is no reaction arising from extra currents; that the iron of the electro-magnet is in a condition of magnetic saturation, so that the laws of Dub and Müller are applicable, and finally that the exterior circuit R is perfectly insulated. When these conditions do not exist, the above conclusions are not valid, and calculation proves that the resistance of the helix should be considerably re-

---

the advantage, because it is in this one that the resistance is so great compared with R, that this latter value does not affect so largely the value $(R+H)^2$ the divisor of $t^2c^{\frac{3}{2}}$.

duced. The experiments of M. Hughes have demonstrated this. And these have been furthermore confirmed by Lenoir on a telegraph line between Paris and Bordeaux, which required very rapid alterations of magnetizing and demagnetizing.

It is impossible therefore to establish for electro-magnets a formula which shall express exactly the conditions of maximum to the resistance of helices; but considering the conditions admitted in the preceding formula, and allowing as experiment shows, that the magnetic attraction increases in a ratio more rapid than the square of the intensity of the current, when the iron core is not saturated, we may conclude, as we shall see further on, that from the circumstance alone of rapid charging and decharging the magnet, that the resistance of the helix should be considerably diminished. But a still greater reduction is called for by the action of derived currents on the lines. A telegraph line of 500 kilometers from Paris to Bordeaux required a reduction in the resistance of the electro-magnet to 40 km.

All the deductions we have thus far established are, therefore, at fault in such applications of electro-magnetism. But such is not the case in the mechanical applications where the circuit is protected, where the magnetism can be freely developed in the iron core, and where the iron is selected with reference to its capacity for saturation.

We shall have occasion presently to examine the condition of the magnetic core, but in order to have done with the laws previously stated, we will consider for a moment the conditions of maximum effect of an electro-magnet introduced into one of the parts of a derived circuit.

In considering the most simple case, that of a single derivation u established upon a circuit whose resistance is l with a common resistance R starting from the battery, we shall find that the attractive force of the electro-magnet interposed upon l will be:

$$A = \frac{E^2 u^2 t^2}{[R(u+l+H)+u(l+H)]^2}$$

And if we substitute for t and H their values previously found, we arrive at an expression, considering g as a variable, which corresponds to the conditions of maximum:

$$(9)\qquad \frac{gg^2}{f^2}\left(l+\frac{\mathrm{R}u}{\mathrm{R}+u}\right)=\frac{\pi ba(a+c)}{g^2}$$

Causing the thickness a of the helix to vary while g remains constant, the conditions of maximum are represented by:

$$\frac{gg^2}{f^2}\left(l+\frac{\mathrm{R}u}{\mathrm{R}+u}\right)=\frac{\pi ba^2}{g^2}$$

In the first of these equations, the second member represents the resistance of the helix, while the first member is the total resistance of the exterior circuit expressed in units of the same order as those giving the length of the wire of the helix. But this *total* resistance is not an increased value. It is represented in fact by

$$\mathrm{R}+\frac{lu}{l+u}.$$

The total resistance here should be considered as if the part common to both derived currents were represented by l and as if the really common part R were only a derivation.

In the second equation the first number represents as before the total resistance of the circuit taken inversely; but this total resistance considered as the resistance of an insulated line, should be less than that of the helix in the proportion of 1 to $1+\frac{c}{a}$ in order to satisfy the conditions of the maximum effect.

We may conclude then that the laws of maximum electro-magnetic action on circuits subjected to derivations, are the same as those relating to simple circuits, by supposing that the resistance R stands for the total exterior resistance, with its branches, and admitting that this total resistance is considered *as though a battery were substituted in the circuit of the electro-magnet.* Now as the total resistance of a circuit thus branched is less than the resistance of the original line, the helix should have a less resistance than this latter. All the formulas have been verified by experiment, as we shall see.

When the derived circuits have a feeble resistance, and when the elements of the battery may be arranged at pleasure, calculations will lead to a conclusion analogous to that just reached, but of a converse kind. It is when the combination of cells is such as to make the battery resistance equal to the total resistance of the circuit, that the best results are obtained. But if after establishing a permanent arrangement of the battery, a series of branches are started from the poles of the battery, and the maximum effect upon the separate circuits is sought, as often happens in practice, the conditions of resistance of electro-magnets interposed in the derived circuits are quite different from those heretofore considered. In this case the magnets, in place of having a resistance less than that of the battery, will have a greater resistance, and greater also in proportion to the number of branches. This is easily understood when it is considered as was said above, that the resistance in the battery should always be equal to the sum total of the derived circuits, and that this total resistance becomes less in proportion as there are more branches, so it is necessary to increase the resistance of each individual branch to compensate for the number. If the derived circuits, with their electromagnets, were all equal, this increase would be proportioned to their number, for the formula for intensity of the current on each branch would then become

$$\frac{n\mathrm{E}}{xn\mathrm{R}+\mathrm{H}},$$

in which x represents the number of branches. But if the derived circuits are of unequal resistance, and if b stand for the number of cells united for *quantity*, and a the number joined for *tension*, the preceding formula will become for two branches, u and H:

$$\frac{a\mathrm{E}}{\frac{a}{b}\mathrm{R}\left(1+\frac{\mathrm{H}}{u}\right)+\mathrm{H}},$$

and the conditions of maximum correspond to

$$\frac{a}{b}R\left(1+\frac{H}{u}\right)=H, \text{ or to } H=\frac{aRu}{ub-aR}.$$

When $u=H$ then $H=2R\frac{a}{b}$. We shall find later an application of these principles.

IV.—Application of the Laws of Maxima to the Construction of Electro-Magnets.

The different laws and formulas which we have established enable us to readily solve the problems relating to electro-magnetic attractions. But it becomes necessary here to introduce the law of Müller relative to the saturation of magnets; a law which establishes that in order to develop in two electro-magnets the same fractional part of their maximum force, it is necessary that the products of the intensity of the currents which charge them multiplied by the number of turns *in their helices* respectively, should be to each other as the $\frac{3}{2}$ power of their diameters.

This may be thus formulated:

$$\frac{\mathrm{I}l}{\mathrm{I}'l'} = \frac{\sqrt{c^3}}{\sqrt{c'^3}}$$

It is easy to see how, from this formula, it becomes easy to determine the required conditions for an electro-magnet of given diameter or power, not only for furnishing all the force of which it is susceptible, but so that the laws of Jacobi, Dub and Müller shall be applicable. It will suffice if two of the terms in the last formula be determined by experiment. There can be obtained from a *standard electro-magnet* in which the power is varied by varying the current, and the forces produced are proportioned to the squares of the intensities of the current.

Experiments made by the writer with an electro-magnet, the iron core of which had a diameter of $0.^{m}01$ and the helix a resistance of 200^{km}, and which was placed in a circuit of 118600^{m}, it was found that the ratio in question could be obtained when the battery consisted of 20 Daniell cups. As the conditions of this magnet were known, it was easy by means of the formulas which have been given to establish the constants, and from that time to have terms of comparison to be used in calculations.

Now we will proceed to show how the preceding equation united with the equations

$$t=\frac{mc^2}{g^2},\quad H=\frac{2\pi c^3 m}{g^3},\quad I=\frac{E}{2R},\quad R=H$$

aid us to solve the problems of which we have spoken in determining the values of the diameter c in relation to the quantities E and R.

If in the first equation we consider the accented terms to be known as belonging to the standard electro-magnet, aud if we replace the quantities I and t by their values deduced from the maximum conditions previously discussed, we shall have

$$\frac{\sqrt{c'^3}}{I't'}\cdot\frac{Emc^2}{2Rg^2}=\sqrt{c^3}$$

And as the diameter g is indeterminate and should be satisfied by the condition R=H on the one hand, and $a=c$ on the other, it should be determined in terms of these two quantities. The equation

$$R=\frac{2\pi c^2 m}{g^2}$$

will serve the purpose.

Inasmuch as g is indeterminate and constantly variable, the term R should be reduced to a function of g. This is afforded by the value

$$g^2=\frac{f^2\sqrt{2\pi c^2 m}}{\sqrt{qR}}.$$

Now substituting this for g^2 in the preceding equation, it becomes:

$$c=\frac{E}{f\sqrt{R}}\left(\frac{\sqrt{c'^2 qm}}{2I't'\sqrt{2\pi}}\right)$$

in which the quantity in parenthesis is a constant which varies according to the system of measurement employed, but in which $m=12$, $q=375000$, and $\pi=3.1416$, and in which the other quantities may be regarded as given, since they relate to an electro-magnet working under known conditions.

On the other hand, in applying the same transformations to the value $\frac{\sqrt{c'^2}}{I't'}$ that we have to $\frac{\sqrt{c^2}}{It}$ we arrive at the value

$$c = c' \frac{E}{E'} \frac{\sqrt{R'}}{\sqrt{R}} \frac{f'}{f}.$$

As $\frac{f'}{f}$ is practically equal to unity, we can relieve the expression of the factor $\frac{f'}{f}$ and consequently the formula simplifies to

$$c = \frac{E}{\sqrt{R}} K \tag{10}$$

K being a constant with different values according to the unit adopted.

If E be expressed in terms of the ordinary standard the single Daniell cell, and if R be expressed in meters of telegraph wire, then K=0.172175 and the value is expressed in fractions of a *meter.*

In referring K and R to the system British Association units, K = 0.01595

The diameter c being known, all t other elements can be easily determin for maximum conditions by means of t formulas previously given, which expre the values of g, b, t and H.

To know the value of the attracti force A, it will suffice to determine t value of $I^2t^2c^{\frac{3}{2}}$, remembering that $I=$ and that the values of t and c are giv by the formulas (6) and (10); and th to get this force expressed as weight it necessary to refer to the standard electr magnet which gives for a consta 0.0000855.*

The value becomes

$$(11) \qquad A=\frac{I^2t^2c^{\frac{3}{2}}}{0.0000855} \text{ grams.}$$

The important results deduced fro formula (10) may be thus enumerated:

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* This coefficient is the force of the standard ma net as expressed by the above formula, measured grams; the force for a distance of 1 millimeter bei 26.85 grams.

1. For equal resistances on the circuit, the diameters of electro-magnets of maximum effect should be proportional to the electro-motive forces employed.
2. For equal electro-motive forces, these diameters should be in the inverse ratio of the square roots of the resistances of the circuit and battery.
3. For equal diameters, the electro-motive forces should be proportional to the square roots of the resistances of the circuit.
4. For a given electro-magnetic force, and with electro-magnets under conditions of maximum effect, the electro-motive forces of the batteries should be proportional to the square root of the resistances of the circuit. (See formula 12.)

The preceding formulas also lead to the easy solution of many problems which frequently present themselves in practical applications of electricity, and particularly in calculating directly the force of a battery, and the dimensions of an electro-magnet to afford a given attractive force on a circuit of given resistance. It is true that the results obtained are not always in accord with the calculation, by reason of the nature of the iron core which may be more or less suitable for ready magnetization, and by reason of the more or less complete saturation of the magnet; but we can always get a fair approximation, and that is considerable gained.

In order to solve the problem in question, we will determine first the fourth deduction above mentioned, and proceed to demonstrate it. This is to determine a value of the electro-magnetic attractive force in terms of the electro-motive force of the battery and the resistance of the circuit.

If we consider the expression $I^2 t^2 c^{\frac{3}{2}}$ which represents this force, we find that by substitutions* in the values of I, *t* and *c*, it becomes

---

* The substitutions referred to are:

$$I^2 = \frac{E^2}{4R^2}.$$

$$\frac{E^{\frac{3}{2}}}{R^{\frac{9}{4}}} \cdot \frac{Q}{f^{2}}$$

in which Q is a constant equal to 2228 (the Daniell cell being the unit of electromotive force, and the resistances being given in meters of telegraph wire).

Now, in estimating the value of the attractive force, we arrive at the relations

$$(12) \qquad \frac{E^{\frac{9}{2}}}{E'^{\frac{9}{2}}} = \frac{R^{\frac{9}{4}}}{R'^{\frac{9}{4}}} \text{ or } \frac{E}{E'} = \frac{\sqrt{R}}{\sqrt{R'}}$$

As in the values of E and R the numbers n and n' of the elements are found, we can easily calculate these numbers, knowing the values of the constants e and

---

$$t^2 = \frac{E\sqrt{R}}{f} \quad 123903.$$

$$I^2 t^2 = \frac{E^2}{f^2 R^{\frac{3}{2}}} \quad 30976.$$

$$c^{\frac{3}{2}} = \frac{E^{\frac{3}{2}}}{R^{\frac{3}{4}}} \quad 0.07195.$$

$$A = I^2 t^2 c^{\frac{3}{2}} = \frac{E^{\frac{9}{2}}}{f^2 R^{\frac{9}{4}}} \quad 2228.$$

element employed, for we have preceding equation :

$$\frac{ne}{n'e'} = \frac{\sqrt{n\rho + r}}{\sqrt{n'\rho' + r'}}$$

accented quantities relate to the standard electro-magnet known, it is easy to deduce preceding formula the value of ly requires the solution of an of the second degree with one quantity.

problem now under discussion

$$\frac{0.002297}{26.85}=0.00008555.$$

The quantity F′ represents in the standard magnet the value $I^2t^2c^{\frac{3}{2}}$, and if we assume

$$\frac{ne^{\frac{9}{2}}}{(n\rho+r)^{\frac{9}{4}}}\frac{Q}{f^2}=PK$$

we can easily deduce the value of *ne*, which will be

$$ne=\sqrt{n\rho+r}\sqrt[3]{\sqrt[3]{\frac{f^4P^2K^2}{Q^2}}}$$

As Q and K are constants they may be removed from under the radical sign, and the expression easily reduces to

$$\frac{n^2e^2}{n\rho+r}=\left(0.0225\sqrt[3]{\sqrt[3]{f^4P^2}}\right)^2$$

The quantity in parenthesis which may readily be calculated, may be represented by A, and we obtain

$$n=\frac{A^2\rho}{2e^2}+\sqrt{\left(\frac{A^2\rho}{2e^2}\right)^2+\frac{A^2r}{e^2}}.$$

The values of ne and $n\rho$ being determined, it becomes easy to calculate the dimensions of an electro-magnet by means of the formulas already given.

In the preceding calculations the resistance of the circuit is supposed great enough to require that the battery employed should be arranged for *intensity;* but if the resistance is so small that the battery may be arranged for *quantity*, the calculations will require some modification. Two cases present themselves; the resistance R may be nothing; or it may be simply less than nr. In the first case we cannot obtain determinate values for a and b (the first representing the number of rows of cups in the battery, and b the number of cups in each row), for the internal resistance of the battery which is then $\frac{a}{b}\rho$, and the resistance H of the helix, being two indeterminate quantities which should be equal, we can assign values at pleasure between the limits corresponding to the values arising from the condition of the battery being arranged entirely for intensity or entirely for quantity.* But we can obtain the value ab or the total number n of the elements by the preceding formulas, which give

$$ab=\frac{\rho}{e^2}\,0.000506\,\sqrt[3]{\sqrt[3]{P^4 f^8}}$$

or

$$ab=\frac{\rho}{e^2}\left(0.0225\,\sqrt[3]{\sqrt[3]{P^2 f^4}}\right)^2$$

---

* This appears clear from the following calculation: The attractive force of an electro-magnet may be represented by I^2H, and when the battery is arranged in series, this expression becomes

$$A=\frac{a^2E^2H}{\left(\frac{a}{b}\rho+H\right)^2}=\frac{a^2E^2H}{4\frac{a^2}{b^2}\rho^2}$$

Now, suppose the battery to consist of 24 elements, each having a resistance of 12, then the electromotive force being equal to 1, when the elements are united for intensity,

$$A=\frac{1\times 288}{4\times 12^2}=0.5,$$

when united for quantity,

$$A=\frac{24^2\times 1\times 0.5}{4\times 12^2}=0.5,$$

and when arranged so that $a=b$, then

$$A=\frac{24\times 1\times 12}{4\times 12^2}=0.5,$$

all the values being identical.

See also Chapter IX of this essay.

Under these conditions the value of c is determinate, and the formula gives

$$(13) \qquad c = \frac{e\sqrt{ab}}{\sqrt{\rho}}\, 0.173.$$

In the second case, as the resistance ought to be equal to $\frac{a}{b}\rho + r$ in order to satisfy the conditions of maximum effect in the magnet, and as in order to give the resistance of the circuit a minimum value, corresponding to a maximum for I, a resistance based upon that of the electro-magnet, it is necessary that $\frac{a}{b}\rho = r$, we shall be able to determine a and b whenever we know ab or n. This will be determined by the preceding equation, which gives the value of ab, since the value $\frac{a}{b}\rho + r$ becomes then equal to $2\frac{a}{b}\rho$. We have then

$$a = \sqrt{\frac{nr}{\rho}}, \text{ and } b = \sqrt{\frac{n\rho}{r}}, \text{ or } \frac{n}{a}.$$

If, instead of a simple circuit we have

a circuit with x branches starting from the poles of the battery, and upon each of these branches there be placed an electro-magnet, all having the same resistances and the same dimensions, the intensity of the current upon each circuit would be

$$\frac{aE}{x\frac{a}{b}\rho+H}, \text{ or } \frac{bE}{2x\rho},$$

and the value of ab or n would be the same as in the case of the simple circuit multiplied by x.

In case the dimensions of the electro-magnet are all given, and it is desired to determine the size and arrangement of the battery to obtain the force P upon each of the x derived circuits :—

From the assumed conditions, the value of H in the equation

$$I=\frac{aE}{x\frac{a}{b}\rho+H}$$

is known; and we also know that for maximum effect $x\frac{a}{b}\rho$ should be equal to

H. Furthermore, we know that we should have

$$I^2t^2c^{\frac{3}{2}}=PK.$$

Now, as the quantities t^2 and $c^{\frac{3}{2}}$ can be easily calculated, since c is given, the value of I is readily found.

$$I=\sqrt{\frac{PK}{t^2c^{\frac{3}{2}}}};$$

from which we deduce

$$a=\frac{2\,IH}{E} \text{ and } b=\frac{axp}{H}.$$

V.—Numerical Examples, Applying the Foregoing Formulas.

To apply the preceding formulas to some practical cases, we will at first suppose that we wish to determine the best dimensions for an electro-magnet to be worked by a single Bunsen cup of medium size, upon a circuit having no other resistance than that of the helix. We will call the electromotive force 1.86, a Daniell element being the unit and the resistance that of 57 meters of telegraph wire, which is 0.57 ohm. These first given quantities exhibit the necessity of knowing the constants for the different batteries in use. They will be given further on.

From formula 10 we shall have for c the diameter of the iron core:

$$c=\frac{1.86}{\sqrt{57}}0.172175=0.^{m}0424.$$

Each of the branches will have then a diameter of $0.^{m}0424$ and a length of $0.^{m}255$. The diameter g of the wire of the helix will be, by formula (7),

$$g=\sqrt{1.4\sqrt{\frac{0.0424^{3}}{57}0.00020106}}=0.^{m}004865$$

which includes the insulating cover. The wire alone would be $0.^{m}00336$ which is the value of g divided by f or 1.4.

The length of the wire would be by formula (5) $243.^{m}$, and the attractive force expressed as a weight at one millimeter, from the formula

$$A=\frac{I^2t^2c^{\frac{3}{2}}}{0.0000855} \text{ will be } 23.^{k}112.$$

If the quantity R is expressed in ohms instead of in meters of telegraphic wire, the constant of formula (7) should be 0.0000020106 instead of 0.00020106, so that the value of g would be

$$g=\sqrt{f\sqrt{\frac{c^3}{R}0.0000020106}}.$$

The number of spiral turns is to be calculated by formula (6).

Suppose now that this electro-magnet be inserted upon a line of 100 kilometers, which with the resistance of the necessary battery composed of 20 Daniell elements will form a circuit of 118620 meters resistance (measured in telegraph wire) ; we shall have

$$c=\frac{20}{\sqrt{118620}}0.172175=0.^{m}01,$$

or in electrical units

$$c=\frac{21.58 \text{ volts.}}{\sqrt{1186 \text{ ohms.}}}0.015057=0.^{m}01.$$

Each of the branches will then have a

diameter of 0.^{m}01, and a length of 0.^{m}06. The diameter of the wire will be 0.^{m}0002597, including the covering, and 0.^{m}0001583 without it, and the length will be 1116 meters. The attractive force equals 26.85 grams.

The different formulas show why electro-magnets that are introduced into long circuits should have small dimensions and have helices of fine wire; and why, on the contrary, for short circuits, the dimensions should be larger, and the battery be arranged for quantity.

The dimensions now to be proposed for an electro-magnet worked by a single Bunsen cell will appear to most people rather large; but they would be still greater if iron of a lower degree of magnetic saturation were to be employed. Thus a tubular electro-magnet having a diameter of 0.^{m}10, a length on each arm of 0.^{m}30, thickness of tube 0.^{m}01, has been made to support a weight of 160 kilograms when charged by a single Bunsen cell. The helix being a copper wire 4 millimeters in diameter (not including the covering), 182 meters long and wound in 482 spiral turns. The poles of the magnet were not even furnished with an iron stopper.

With an ordinary electro-magnet $0.^{m}02$ in diameter, wound with copper wire one millimeter in diameter, the writer has never been able to obtain with a single Bunsen cell more than 12 kilograms of attractive force at contact with the poles.

We will assume now that we are to obtain a given force on a circuit of given resistance; that the attractive force is to be 273 grams at a millimeter distance; the circuit to have a resistance of 500 ohms, 50 kilometers of telegraph wire), to be charged with a single bichromate cell. In the proposed battery (potassium bichromate with sand) the electromotive force is 2 and the internal resistance about 10 ohms.

Applying the formulas in Chapter IV, we have

$$A=0.0225\sqrt[3]{\sqrt[3]{1.37^4\times 273^2}}=0.09$$

$$\text{and } A^2=0.0081.$$

$$n=\frac{8.1}{8}=\sqrt{\left(\frac{8.1}{8}\right)^{2}+\frac{0.0081\times 50000}{4}}$$
$$=11.125$$

from whence

$$c=\frac{11.125\times 2}{\sqrt{61125}}\times 0.173=0.^{m}01553.$$

This gives for the length of each helix o.^{m}0932. Diameter of wire without covering, 0.^{m}0002842. With its covering, 0.^{m}0003894. Length of the wire, 1861 meters. Number of turns, 19078. Intensity of current, 0.0001859. The value $c^{\frac{3}{2}}=0.001935$.

Squaring the values of I and t and multiplying by $c^{\frac{3}{2}}$ we get for the electro-magnetic force 0.0243778517. Comparing this value with that of the standard electro-magnet, which is 0.002297, we find the ratio to be 10.6, which is very near the ratio demanded. The attractive force in grams of the standard being 26.85, and the force required above being 273 grams.

We will now suppose it is desired to obtain a force of 200 grams on each of six electro-magnets all connected with a battery of the same kind as the preceding.

The total number of cells will be given by the formula :

$$ab=\frac{6\times 1000}{4}\times 0.000506^{2}\sqrt[3]{\sqrt{200^{4}\times 1.4^{3}}}$$

$$=10{,}778,$$

or say 11 cells. But as this number is not readily divided into groups, we will take 12. With this number of cups we can arrange them in 3 rows of 4 cups, or in 2 rows of 6 cups each, but in either case we shall have

$$c=\frac{\sqrt{12}}{\sqrt{1000\times 6}}\times 2\times 0.173=0.^{\text{m}}0153$$

and consequently the length of each branch of the electro-magnets will be $0.^{\text{m}}0918$, or about a tenth of a meter.

Now we will compare the values obtained under the supposition of the two different arrangements of the 12 cells.

1st, when $a=3$ and $b=4$.

$g^2=0.000000560075$.
$g=0.0007484$.
$\frac{g}{f}=0.0005346$.
$H=482^m$
$t=5015$, $t^2=25150225$.
$I=0.000666$.
$I^2=0.000000443556$.
$c^{\frac{3}{2}}=0.001892$.
$I^2t^2=11.155533$.
$I^2t^2c^{\frac{3}{2}}=0.021084$.
$A=247$ grams.

2d, when $a=2$ and $b=6$.

$g^2=0.00000083986$.
$g=0.000916$.
$\frac{g}{f}=0.0006543$.
$H=321^m$.
$t=3345$, $t^2=11189025$.
$I=0.001$, $I^2=0.000001$.
$c^{\frac{3}{2}}=0.001892$.
$I^2t^2=11.189025$.
$I^2t^2c^{\frac{3}{2}}=0.0211686353$.
$A=247$ grams.

It is not necessary, however, to conclude that in order to maintain a good condition of saturation in the magnets, that we ought to vary their dimensions according to the resistance of the exterior circuit. We can for some applications keep to the same dimensions for the magnet, by varying the force of the battery and the dimensions of the wire of the helix. Since the electromotive force of the battery employed, for the same diameter of electro-magnet, and a given electro-magnetic force is proportional to the square root of the exterior resistance of the circuit, we may conclude that if we augment the electromotive force E in a proper ratio, we may as the resistance of the circuit increases, continue the use of an electro-magnet of the same diameter and having the same force; consequently if instead of inserting our standard magnet of $0.^{m}01$ diameter in a circuit of 100 kilometers, we introduce in a circuit of 400 kilometers with double the number of cells, we shall have very nearly the same effect produced. But it would be neces sary to change the dimensions of the wire, for the diameter of the magnet remaining the same, the diameter of the wire should vary in the inverse ratio of the fourth root of the resistance of the exterior circuit. It would be necssary, then, in the example cited that this diameter should be to the diameter of the wire of the standard magnet $0.^{m}0001583$.

as $\sqrt[4]{100000} : \sqrt[4]{400000}$,

or as $17.8 : 25.1$,

which gives 0.000112. We see that for telegraph relays the assigned dimensions may be preserved.

It has been asserted above that in doubling the number of elements of a battery, we shall obtain *nearly* the same force upon a circuit of 400 kilometers as previously upon a circuit of 100 kilometers. The qualification *nearly* is necessary, for as the resistance of the circuit, the resistance of the battery is also counted, and as the latter varies with the number of elements employed, the real resistance of the circuit is 437240 meters instead of 400000 (400^{km}). Now this is a little less than 4 times 118620^{m} which represents the resistance of the first circuit, so that to obtain the same effect in the two cases it would be necessary that the number of elements (20) should be raised to 38.4 (say 39) instead of 40.

We will now consider the case of two small electro-magnets, each having 2200 meters resistance, of No. 15 wire, and connected with a Daniell battery of 8 cups arranged for intensity. Experiment proves that the force obtained from each would be 70 grams at a millimeter distance. Consequently the force developed by the pair would be 140 grams. Now if in place of the two magnets only one had been employed, the force would have been 200 grams. There is then a loss of 60 grams by the use of the second magnet, although both of them are connected directly with the poles of the battery. It would seem at first sight as though there were some defect in the electrical connections, but we will proceed to show that calculation verifies the above result.

Applying Ohm's formulas to the two cases, we find: 1st, that in the case of the single electro-magnet, if we represent the electro motive force of the Daniell cell by 5973, the intensity of the current will be 4.95; 2d, that, in the case of the two electro-magnets forming two branches the intensity is 2.79.

The forces of the electro-magnets under these two arrangements are as the squares of these numbers 4.95 and 2.79, and if we estimate the force of the electro-magnet in a simple circuit at 200 grams, the force of the two others would be given by the formula

$$\frac{\overline{2.79}^2\times 200}{\overline{4.95}^2} = 64 \text{ grams.}$$

Consequently the force of the pair of magnets would be 128 grams against 200 grams for the single magnet.

The result arises from the arrangement of the battery which was not adjusted to accord with the exterior resistance, since its resistance is nearly four times as great as the latter, and is again less than the resistance of the circuit containing the two magnets. The formula

$$\frac{nE}{2n\rho+H},$$

which represents the intensity of the current upon each branch, and which, in case of a battery arranged in series, gives for condition of maximum effect $2\frac{a}{b}\rho=H$, or $\frac{a}{b}\rho=\frac{H}{2}$, shows that in this case the resistance of the battery ought to be half that of each circuit, consequently the number a of the elements in tension should be determined by the formula:

$$a=\sqrt{\frac{8\times 2200}{2\times 931}}=3.074.$$

As we cannot divide a cell of a battery, and as the plan requires that the numbers expressing values of a should be divisors of n, the battery which best lends itself to the several conditions of maximum is the one which most readily admits of division into various groups, and we see that in the case before us the conditions require 3 cups in tension and 3 in quantity. Now under these conditions, the attractive force of the single electro-magnet would be 267 grams, and of the two magnets 316 grams. There is then a gain in the use of the two magnets.

The foregoing examples show the importance of making calculation precede the construction of electro-magnets and the arrangement of the battery.

VI.—EXPERIMENTAL VERIFICATION OF THE LAWS OF ELECTRO-MAGNETISM.

The formulas given in the preceding chapters have all been verified by the writer's experiments, except such as are generally adopted and which present difficulties in verification as we shall see forthwith.

This experimental work seemed the more *important*, as formerly many scientists would not accept the formulas without discussion, and furthermore mathematical calculations are not always convincing. The writer has made many experiments to prove the truth of his deductions and with results as follows:

1st. The experimental demonstration of the principle which establishes the rule that the resistance of the electro-magnet should be equal to that of the exterior circuit is quite difficult by reason of the difficulty of finding wire of different sizes whose conductivities are exactly proportioned to the squares of the diameters. The experiments tried gave contradictory results, and it is proper to say, some that were contrary to the theoretical conclusions, which led in the beginning of these researches to some hesitation in accepting them, although they had been already generally accepted. Meanwhile as the other conclusions have been confirmed by experiment, and as the ill success of those experiments relating to this subject may *have* been due to accidental causes, the principle above stated has been admitted in those cases in which it is really applicable: that is to say when the size and length of the spool or helix having been fixed, it is required to know the size of the wire which should be employed to correspond to a circuit of given resistance. It is a case in which the elements of the construction have been already determined, since the size of the iron core should in the first place be proportioned to the intensity of the current, and since the thickness of the helix should be determined by another important principle.

This is not the same problem as the determination of the resistance of the circuit upon which a given electro-magnet or galvanometer can be profitably employed, without having previously considered its dimensions. In this latter case, the conditions of maximum effect as established by the writer show that, *the resistance of the electro-magnet should be to the resistance of the exterior circuit, as the thickness of* the helix *plus the diameter of the core, is to the thickness of the helix.*

This rule has been established by the following experiments:

Upon a spool whose length between the ends was 0.^{m}061, and with a tube 0.^{m}011 in diameter there was wound with great care two lengths of 60 meters each of No. 15 wire, also another length of 57¼ meters which formed a third helix. These three helices presented their ends outward each distinct from the other so that they could be used separately or together. The first offers a resistance of 1080 ~~1800~~^{m} of telegraph wire; the second had nearly the same so that the two joined made a resistance of 2160 meters; and finally, the third helix added to the two first furnished a total resistance of 3200 meters.

In subjecting this electro-magnet to the test of the writer's electro-magnetic balance, and applying to that pole only which was enclosed by the helix, and exciting the magnet by the current from a

Leclanché battery of 3 cups, each with a resistance of about 400^m, the following results were obtained :

Resistance of exterior circuit.		Helix A. 1080^m.	Helix B. 2160^m.	Helix C. 3200^m.
m.	m.	gr.	gr.	gr.
1200+	0 (1200)	$F=112$	$F'=122$	$F''=112$
1200+	400 (1600)	$F=73$	$F'=92$	$F''=95$
1200+	1000 (2200)	$F=47$	$F'=66$	$F''=70$
1200+	2000 (3200)	$F=27$	$F'=43$	$F''=50$
1200+	3000 (4200)	$F=17$	$F'=29$	$F''=36$
1200+	4000 (5200)	$F=12$	$F'=22$	$F''=28$

The attractive forces F, F', F'' were measured at the distance of one millimeter from the pole.

Now this table shows that the helix B, whose conditions of resistance most nearly accord with the theoretical conditions,

$$\left\{ \frac{2160}{1+\frac{c}{a}}=982 \right\}$$

affords the maximum effect, and it is only when the resistance of the exterior circuit becomes 1600^m or $\frac{3200}{2}$ that the helix of highest resistance C exhibits a preponderance.

With 2 cups of the battery and an exterior resistance of 800^m (represented by the battery), the helix B gave a force of 60 grams, while A and C each gave 57 grams. With a single cup and its resistance of 400, the helix A had the advantage, and the forces were 21 grams for A, 19 for B and 17 grams for C.

These experiments repeated with the galvanometer were yet more decisive as the reader may readily verify by consulting the account published by the author in *Comptes rendus des Séances l'Académie des Sciences*, Aug. 13th, 1877.

2d. In order to demonstrate that upon a branched circuit, the resistance which is to serve as the basis of calculation of that of an electro-magnet is the total exterior resistance *taken inversely*, that is to say as though the generator had been substituted for the electro-magnet —a sensitive Ruhmkorff galvanometer was inserted in a circuit having a very *feeble* generator. The galvanometer had two multipliers, one of 733 kilometers resistance, and the other of 237^{km}. A rheostat was added to this circuit, and a second one to a branch joining the two extremities of the galvanometer wire.

Calling R the circuit of the electrometer, u the galvanometric derivation, l the derived circuit in which the galvanometer was inserted, the equation expressing the condition of maximum effort was

$$l+\frac{Ru}{R+u}=\frac{\pi ha^2}{g^2}.$$

It is true that l cannot well influence this calculation, since the points of branching were the two extremities of the galvanometer; but by means of the two rheostats, the resistances u and R could be so varied as to present a combined *total* resistance, which was equal to, or greater, or less than the less resistant of the multipliers of the galvanometer; so that it sufficed, R being given, to calculate u by the formula

$$u=\frac{RH}{R+H},$$

H representing the resistance of the multiplier.

The results obtained after taking all precautions to preserve proper conditions were as follows:

Derived circuits.	Total resistance.	Multiplier 237^{km}.	Multiplier 733^{km}.
km. km.	km.	°	•
$R=512+272$ $u=86$	78	$I=27\frac{1}{2}$	$I'=24\frac{1}{4}$
$R=512+272$ $u=128$	110	$I=32\frac{1}{2}$	$I'=30$
$R=512+272$ $u=200$	160	$I=36\frac{1}{4}$	$I'=36\frac{1}{4}$
$R=512+272$ $u=256$	193	$I=40$	$I=41$
$R=512+272$ $u=512$	309	$I=46$	$I=51$
$R=512+272$ $u=200$	145	$I=36$	$I=33\frac{1}{4}$
$R=512+272$ $u=512$	260	$I=47$	$I=52$

It will be seen by this table that, as was said above, the multiplier (resistance coil) of greatest resistance has the advantage even where the total resistance of the circuit outside of the galvanometer is nearly equal to the smaller resistance coil; and it is only when this total resistance falls below 160^{km} or 145^{km}, a point at which the two multipliers have the same sensitiveness that the multiplier of least resistance exhibits an advantage. As with the galvanometer experiment, the ratios of the two resistances (the exterior circuit and the resistance coil), ought to be according to the conditions of maximum deduced from calculation 1.9 and 2.425—the resistances of the exterior circuit where the multipliers could be applied to the best advantage, should be 98^{km} for the multiplier of 237^{km}, and 386^{km} for the multiplier of 733^{km}; and the point at which they become equally sensitive ought to correspond to a resistance which is a mean proportional between these two numbers. Now this mean proportional being 193, and as the number furnished by experiment is 160, we may conclude that the principle previously stated has been practically verified. It is capable of further proof by calculating the resistance of *u*, which would equal deflections for the two resistance coils. This resistance is given by the formula

$$u=\frac{R(t'H-tH')}{t(R+H')-t'(R+H)},$$

which gives under conditions established for the galvanometer experiment, 224^{km}, while the experiment indicates 200^{km}.

3d. The principle governing the thickness of the magnetizing helix—that it should be equal to the diameter of the iron core—is readily verified. To demonstrate this experimentally, the writer took three magnets of the same length but of different diameters, as follows: 1st, $0.^{m}02$; 2d, $0.^{m}01$, and 3d, $0.^{m}0065$. Only one pole was brought to act upon the electro-magnetic balance; each spool was wound with No. 16 wire; 23 layers of 111 turns each, or a total of 2553 spiral turns. The wire was closely wound in each case, and the helices had a uniform thickness of $0.^{m}01$.

It follows, therefore, that the dimensions of the 2d magnet alone corresponded with the conditions of maximum effect as previously stated. This magnet had a resistance of 3200 meters, while the larger offered a resistance of 5200, and the smaller one 2800 meters.

The results of the experiments are exhibited in the following table. The battery consisted of from 1 to 3 Leclanché cells, each having a resistance of 400^{m}. The magnetic attraction was estimated at a millimeter distance.

	Resistances of circuit.			Attractive force of the magnets.		
				No. 1.	No. 2.	No. 3.
				0.^{m}02	0.^{m}01	0.^{m}0065
	m.	m.	m.	gr.	gr.	gr.
3 cells.	1200+	0	(1200)	76	112	86
	1200+	1600	(2800)	48	57	(44)
	1200+	2000	(3200)	43	(50)	39
	1200+	4000	(5200)	(28)	29	22
	1200+	10000	(11200)	13	10	8
2 cells.	800+	0	(800)	38	57	46
	800+	2000	(2800)	22	26	(20)
	800+	2400	(3200)	20	(22)	16
	800+	4400	(5200)	(14)	13	10
	800+	10000	(10800)	7	5	4
1 cell.	400+	0	(400)	12	18	15
	400+	2400	(2800)	7	7	(6)
	400+	2800	(3200)	6	(6)	5
	400+	4800	(5200)	(5)	4	4
	400+	10000	(10400)	3	2	2

The table clearly shows that for the same resistance of exterior circuit, and with sufficient intensity of current, the advantage is with the magnet whose diameter equals the thickness of the helix. This advantage is maintained so long as the forces produced through the circuits of different resistances are properly proportioned to the resistances of the electro-magnets; and such conditions only are considered in the formula. It is only when the electric force is so feeble that the increase of magnetic ac tion with the increase of diameter is but slightly marked, that the superiority of magnet No. 2 is affected. This is in accoad with Müller's law, for the attractive forces of the magnets are proportional to their diameters only when the magnets are charged nearly to the point of saturation. By the term saturation is meant that magnetic state which the magnet would retain if it were hardened steel instead of iron. When the force developed is much below this, it is dependent chiefly upon the intensity of the current, and that is naturally the strongest on the circuit of least resistance.

The numbers in parenthesis in the preceding table indicate the forces corresponding to maximum conditions relative to the circuit, and these conditions have been established on the hypothesis that the resistance of the exterior circuit was equal to the resistance of the helix, and in the construction of these electro-magnets a given thickness of helix was the starting point. If it had been based upon maximum conditions of a given electro-magnet without consideration of dimensions the preceding law would assert itself still more, for the maximum resistances of the exterior circuit become 2600^m for the larger magnet, 1600^m for No. 2, and 1400^m for No. 3. The attractive forces of the three magnets then become:

	With 3 cells.	With 2 cells.	With 1 cell.
For magnet No. 1..	50 gr.	25 gr.	8 gr.
" " 2..	94	46	14
" " 3..	79	41	13

VII.—EFFECTS UPON ELECTRO-MAGNETS OF SATURATION MORE OR LESS COMPLETE.

As was said in a previous chapter, the laws governing electro-magnets can not all be stated with desirable precision by reason of the variable resultant effect of saturation of the soft iron core; but this cause of perturbation is far from being as prominent as some scientists would have us believe, and it interferes with the definite results which they have deduced, much less than the effects of polarization have upon calculated results of electric currents. During the last researches upon electro-magnets, the writer wished to assure himself of the importance of this cause of perturbation, and a large number of experiments were undertaken which seem to be of sufficient interest to be related here, inasmuch as the rapid extension of the application of electro-magnetism renders it daily more important that the best working conditions of electro-magnets should become known.

In the second chapter of this essay some general principles were stated, deduced from the author's experiments, but not much stress was laid upon these experiments as they were not conducted with reference to any law outside of those formulated by Dub and Müller; but it is important that a more definite explanation should now be given.

First it will be shown that having determined that the number 11 is the proper multiplier by which to determine the length of the magnet after its diameter is fixed, it will follow that the attractive force will increase in proportion to the length. So that starting with a given length of wire to represent the resistance of the exterior circuit, and winding it upon electro-magnets of different diameters so as to furnish each with a thickness of helix equal to the diameter of the core, it would be necessary that the lengths should be different and that should satisfy the following conditions:

$$\frac{2\pi bc^2}{g^2}=\frac{2\pi b'c'^2}{g^2}, \text{ or } bc^2=b'c'^2,$$

so that the lengths would be inversely proportioned to the squares of the diameters. In this case the factor m (ratio of length in diameter) is no longer constant, and becomes proportional to the cubes of the diameters.

But then the law which directs that the electro-magnetic force should be proportional to the square of the number of turns of the helix wire, multiplied by the $\frac{3}{2}$ power of the diameter is not applicable, and it becomes necessary to resume the consideration of it so as to make a comparison of such forces among themselves, according to the law which states that these forces are proportional to the squares of the number of turns of the wire, multiplied by the diameters of the cores and the square roots of their length. We shall then have for the same intensity of current:

$$\frac{A}{A'} = \frac{c^2 b^2 c \sqrt{b}}{c'^2 b'^2 c' \sqrt{b'}} = \frac{c^3 b^{\frac{5}{2}}}{c'^3 b'^{\frac{5}{2}}} =$$

$$= \frac{c^3 c'^5}{c'^3 c^5} = \frac{c'^2}{c^2} = \frac{b}{b'},$$

which shows that *the forces are in the inverse ratio of the squares of the diameters, or proportional to the lengths;* always supposing that the iron cores are in the proper condition of saturation to render the laws of Dub and Müller applicable.

In order to make known the modifications required to the laws formulated connecting the state of saturation with the length and diameter, three electro-magnets having diameters of 0.^{m}008, 0.^{m}007 and 0.^{m}006 respectively, were wound with the same length of No. 12 wire, having a diameter of 0.^{m}00059 including its cover This length was 71.^{m}47, and its resistance was equal to 722 meters of telegraph wire or 7.22 ohms; and the spools were so constructed that the thickness of the helix was in each case equal to the diameter of the core. The lengths of the spools were, consequently: the first, 0.^{m}059; the second, 0.^{m}077; and the third, 0.^{m}098; and the number of turns of wire were respectively, 1470, 1677 and 1842. The results given in the table on next page were obtained with a Leclanché battery of the later pattern, varying from 1 to 4 cells, each having a resistance of 113^{m} or 1.13 ohms. The attractive force was measured at the distance of a millimeter.

These results show that conformably to the theory, it is the longest electro-magnet which is generally the strongest, but is in *the same ratio as the length, only for electro-magnets of certain limits as to diameter, and for a certain intensity of current which corresponds probably to the saturation of the magnets.*

This intensity for electro-magnets of $0.^{m}098$ and $0.^{m}077$ varies from 0.001082 0.001030, 0.00143 and 0.00113 in the four series of experiments; but in comparing the electro-magnets of $0.^{m}098$ and $0.^{m}059$, the proportion in question is no longer related to the intensity of the currents and the ratio of the forces is less than the ratio of the lengths. Further than this it may be remarked, that the forces of these electro-magnets is so

Exterior resistances.	Force of magnet. 0^m,098.	Ratios	Force of magnet. 0^m,077.	Ratios	Force magne 0^m,05
m m m	gr.		gr.		gr.
452+ 0 (452)	225	1,018	221	0,9210	240
452+ 300 (752)	151	1,049	144	0,9660	149
452+ 400 (852)	134	1,0635	126	0,9770	129
452+1000(1452)	73	1,0900	67	1,0307	65
452+2000(2452)	36	1,161	31	1,0333	30
452+3000(3452)	21	1.235	17	1,0630	16
452+4000(4452)	14	1,272	11	1,1000	10
339+ 0 (339)	169	1,0432	162	0,953	170
339+ 300 (639)	109	1,0792	101	1,010	100
339+ 400 (739)	95	1,092	87	1,0117	86
339+1000(1339)	50	1,163	43	1,0238	42
339+2000(2339)	23	1,2105	19	1,0555	18
339+3000(3339)	13	1,300	10	1.000	10
339+4000(4339)	8	1,333	6	1,000	6
226+ 0 (226)	100	1,111	90	1,000	90
226+ 300 (526)	60	1,154	52	1,0196	51
226+ 400 (626)	52	1.1818	44	1,0232	43
226+1000(1226)	26	1,3000	20	1,000	20
226+2000(2226)	11	1,375	8	1,000	8
226+3000(3226)	6	1,500	4	1,000	4
226+4000(4226)	4	2,000	2	1,000	2
113+ 0 (113)	35	1,2070	29	1,036	28
113+ 300 (413)	19	1,2666	15	1,071	14
113+ 400 (513)	16	1,3333	12	1,0909	11
113+1000(1113)	7	1,1666	6	1,200	5
113+2000(2113)	2	1,0000	2	2,000	1
113+3000(3113)	1	1,0000	1	"	0
113+4000(4113)	0	"	0	"	0

governed by the state of saturation of the core that for the highest electric intensities, and upon circuits of lowest resistance, it is the shortest and largest electro-magnet that gives best results. Conversely the narrowest and longest magnet exhibits its advantage more and more in proportion as the electricity diminishes, whether this diminution is caused by lessening the number of cells of the battery, or by increasing the resistance of the circuit. The importance of such variations can be estimated by the relations of the forces exhibited in the second and fourth columns of the preceding table. It is readily understood why it should be so, as for very high intensities, the diameter of the longer electro magnet is not in proper proportion to this intensity, and it has passed its point of saturation when the short and large magnet would have just attained it. On the other hand, the advantage of the magnet of small diameter, under the action of feeble currents, is explained by this consideration; that the magnetic mass of the electro-magnet being sufficiently great compared with the electric force, this force affects beneficially the greater number of the turns of the helix wire. We may conclude, then, that the dimensions to be given to an electro-magnet ought to depend essentially upon the electric force which excites it, and upon the resistance of the circuit in which it is to be placed. *When the circuit is long and the electric source is of feeble energy, the magnet should be long and of small diameter.* When, on the *contrary, the circuit is short and the electric current intense, the iron core should be of large diameter.*

This is expressed otherwise by the formula $c = \frac{E}{\sqrt{R}} 0.173$, which is offered by the writer to aid in determining the diameters of electro-magnets when the other conditions are known.

In regard to the influence of the condition of the magnetic saturation of the iron, it is difficult to formulate its effects. Joule, Müller and Robinson all long ago recognized the fact, that at the commencement of the current and while the magnetic state is yet far short of saturation, *the attractive force instead of increasing as the square of the intensity the current augments in a much higher ratio, exceeding the third or even the fourth power of the intensity.* But the fact is also verified, *that in proportion as the electro-magnetic force is developed this ratio diminishes rapidly to the point of saturation, remains stationary for a moment, and beyond this point diminishes till the forces are in simple ratio with the intensity of the current.*

If the magnetic force thus varies as it is being developed, similar results should be exhibited when it can be completely developed in magnets whose dimensions admit of different degrees of saturation for the same intensity of current. This hypothesis can be verified by the results of the experiments already cited.

Considering the case of the three magnets in the last example, in which the forces were developed by currents of different intensities; *we find that there is for each of them a degree of intensity for which the attractive force varies as the square of this intensity, and that above and below this limit it increases in a more or less rapid ratio. Also, that this limit varies with the dimensions of the electro-magnet.*

In preparing from these results the table which follows, we see: 1st, That it is the electro-magnet B which best conforms to the law of the squares of the electric intensities. 2d, That the larger magnet C affords the highest ratio of increase. 3d, That the smallest magnet A furnishes the lowest ratio. 4th, That the ratio of the forces for the three magnets varies rather more rapidly than it should to accord with the law of squares of the intensities, as the intensities become weaker, whether from reducing the number of cells or from increasing the resistance.

It is certain that these ratios, notwithstanding their larger value, correspond more nearly to the squares of the intensities than to their cubes. We have, for example, between the first and last experiment of the first series, 85600 instead of 19423; but we will remark that the three magnets have diameters not widely different; that they are nearly in the same condition as to saturation, and that the forces have been measured at the moment of maximum magnetization.

It is evident that we should not have obtained the same results with magnets differing more in their diameters, nor if the forces had been measured instantly at the moment of magnetization, and during a closing of the circuit. In such a case we should, perhaps, be able to get a higher ratio than 85600. Upon this principle is based the action of the sluggish electro-magnets employed in some of the printing telegraphs, and which are slow in action only because their mass being relatively large, considerable time is consumed in charging

The following table exhibits the ratios previously alluded to:

No. of cells.	Ratios of square of intensity of current.	Ratio of forces. A 0^m,098.	Ratio of forces. B 0^m,077.	Ratio of forces. C 0^m,059.
4 Cells.	1,576	1,49	1,54	1,61
	1,797	1,68	1,75	1,86
	3 429	3,082	3,30	3,70
	7,309	6,25	7,13	8,00
	12,640	10,71	13,60	15,00
	19,423	16,07	20,09	24,00
3 Cells.	1,645	1,55	1,60	1,70
	1,896	1,78	1,86	1,97
	3,773	3,38	3,77	4,05
	8,323	7,35	8,52	9,44
	14,650	13,00	16,20	17,00
	22,753	21,12	27,00	28,33
2 Cells.	1,733	1,66	1,73	1,76
	2,022	1,92	2.04	2,09
	4,222	3,84	4.50	4,50
	9,670	9,09	11,25	11,25
	17,343	16,66	22,50	22,50
	27,242	25,00	45,00	45,00
1 Cell.	1,847	1,84	1,93	2,00
	2,187	2,19	2.42	2,55
	4,829	5,00	4,83	5,60
	11,527	17,50	14,50	28,00
	21,094	35,00	29,00	"
	33,529	"	"	"

From the numerical results given in this table, we are led to conclude that the law making the attractive forces proportional to the square of the intensities of the currents, holds good within certain limits, and under certain indications; and that the electro-magnets over which the currents are broken at short intervals, fail more or less. Now as this case is involved in the important question of the magnetizing helix, it would seem opportune to consider it from this new point of view; not to establish the conditions of maximum effect which have been already determined, but to find out in what way they are to be modified to suit certain cases.

The question is this: When the electro-magnetic force increases in a more rapid ratio than that of the squares of the intensities of the current (say as the cubes for instance), should the resistance of the magnetizing helix be greater or less than that of the exterior circuit?

To answer this question it will suffice to change in the formula giving the value of electro-magnetic force the exponents of the values of the intensity, or in other words, change I^2 to I^3. We obtain then this expression:

$$8f'^2\pi ba(a+c)=4qRg^4$$

which, if g varies, gives for a maximum

$$\frac{\pi ba(a+c)}{g^2}=\frac{qRg^2}{2f'^2},$$

or

$$H=\frac{R}{2}.$$

If a is the variable quantity, the conditions of maximum correspond to the equation

$$\frac{qRg^3}{f'^2}=\frac{\pi ba\left(2a+\frac{c}{2}\right)}{g^2}.$$

These two equations show that when the forces are proportional to the cubes of the intensity of the current, *the helices should offer less resistance than the exterior circuit; only half as much if* g *is the varible quantity, and in the ratio of* $a+c$ *to* $2a+\frac{c}{2}$ *when* a *is the variable.*

We may conclude, then, that upon circuits subject to frequent interruptions, the resistances offered by the magnets should be lessened in proportion as the intervals of closing the circuit are shortened. And it is for this reason as much as for that of defective insulation and of extra currents, that Hughes first, and subsequently telegraph engineers, reduced considerably the resistances of magnets upon long circuits.

It would be equally interesting to know in what way the resistance of the electro-magnet should be modified in the case where the point of saturation being passed, the force increases less rapidly than the square of the intensity of the current. If we suppose that this increase is simply in the ratio of the intensity, then there is no maximum possible, and we can with advantage increase the resistance of the magnets beyond the limits which have been assigned.

In seeking to determine how the conditions of maximum effect which involve the thickness of the helix should be modified to suit the conditions of defective saturation of the magnetic core, we find that we can increase this thickness, and that while the attractive force increases as the cube of the intensity, the thickness of the helix may with advantage be double the diameter of the core. The expression

$$\frac{E^3 t^2 c}{\left(\frac{\lambda \pi b a (a+c)}{g^2}\right)^3}$$

is a maximum if c is variable when $a = 2c$. On the other hand, there is no maximum when the forces are simply proportional to the intensities of the current.

VIII.—CONDITIONS GOVERNING THE CONSTRUCTION OF ELECTRO-MAGNETS.

The calculation of the elementary parts of electro-magnets is not all that is necessary. To secure the best results, it is also necessary to take into consideration the secondary causes which can influence them and their sources of action.

This question will now be considered, and will recall the conclusions reached by the writer, from numerous experiments tried during the past twenty years.

1st. *Conditions of electro-magnetic force which are dependent upon exterior causes.*—Descartes and many later physicists have shown that if a mass of iron be brought in contact with one pole of a bar magnet, that the attractive force of the other pole is augmented, and that the increase is somewhat proportioned to the mass. M. Dub, who wished to include a statement of this fact in the laws of electro-magnetism, considers that this increase is a result of the general law, that the force increases with the increase of length of the magnetic core. But this increase should by the law be proportioned only to the square roots of the lengths; whereas, according to the author's experiments, the increase is enormously greater, since the force is frequently more than trebled. Furthermore, the writer has shown that this increase is produced by iron masses of all shapes, some of which do not increase the length of the magnet to a notable extent, and also when not in immediate contact with the magnet proper. It has been observed during these experiments that the development of a magnetic surface has much to do with the phenomena. Now, the author's conclusion is, that the increase of energy is due principally to the effects of magnetic condensation developed by the contact of the two pieces, and that the stimulation of the free pole is a secondary effect, since the two polarities of any magnet bear a constant relation to each other.

This conclusion has been experimentally verified by alternately placing upon a long, soft, iron rod helices of different lengths but composed of the same lengths of wire. The helix which covers the entire rod is the one affording the least attractive force, although it has the greatest number of turns of wire. The helix which has the maximum effect is that which covers only one-third of the length, *measured* from the active pole.

Now, when these same helices are applied to iron rods of the same length as themselves, the effect is altogether different. Then the force increases as the length increases, but not in proportion to the length. The forces seem to increase in an arithmetical proportion, while the lengths are in geometrical ratio; and the rate of this increase seems to bear a direct relation to the number of cells of the battery. Only these last results will be here specified as applying to a particular case.

The effects about to be cited illustrate the action of electro-magnets when charged with a single helix upon one of the. branches only, a kind upon which the author was the first to experiment, and which he calls *electro-aimants boiteux* (lame or crippled magnets), and which are nearly as energetic for the number of coils of wire as the magnets of two helices.

2*d*. *Relations of the electro-magnetic force to the form and disposition of the armatures.*—The author sums up his conclusions from his experiments in the following manner:

(*a*). The attractive force of electro-magnets, whether great or small, is greatest when that surface of the armature which is directly acted upon is most developed, and when the mass of iron exposed to the magnetic influence is most completely subjected to the magnetic forces.

(*b*). It results from this that the attraction of electro-magnets of two branches for flat prismatic armatures is greatest when the armatures are presented flatwise, if at a little distance from the magnet, while the converse is true for the condition of contact, and the greatest force is manifested when the armature is presented edgewise. .For the attraction at a distance the ratio of the effects of the two positions may be as 59 to 92.

(*c*). The arrangement by which the armature is caused to rotate about a pivot near one of the poles is better than that by *which it is* allowed to move parallel to the line joining the two poles, as when it is made a cross-bar at the end of a tilting lever. The advantage of the former method is especially manifested in the case of magnets with a helix on one pole only, in which the forces developed under the two methods are in the ratio of 125 to 64.

(*d*). Prismatic armatures are attracted with a force proportioned to their extent of surface; but the *form* of the surface has a great influence, as the mean distance of the whole surface from the poles may vary considerably with the shape. Thus a cylindrical armature is attracted with much less force than one of prismatic form having the same amount of surface; the ratio of the forces being as 44 to 85.

(*e*). By reason of an analogous reaction to this last, the *lateral* attraction of electro-magnets, where the cores project a little way from the helix, is much less energetic than the attraction in the direction of the axis of the cores; the ratio being about as 18 to 33.

(*f*). Armatures made of permanent magnets aid the attraction only when used at a distance from the poles, and are kept parallel to a line joining the two poles. For other positions they are a disadvantage, as magnetic action, when exerted upon steel, is much less than upon iron.

(*g*). The attractive force due to the momentary closing of a circuit is, for any given distance of the armature, much greater than that arising from the constant action of the same current when a counter force is opposed to it. This fact may be referred to the effects of living forces, and to the polarization in the cell. The ratio of attractive forces is as 136 to 95.

(*h*). When the force of an electromagnet is divided among several armatures, the total attractive force is augmented, but the force exerted upon any one armature is less in proportion as the number is greater. This increase of total force, however, is manifested only within certain limits, which are reached when the mass of the armatures is equal to that of the electro-magnets.

(*i*). The attractive force between an electro-magnet and an armature which has not been previously employed, is for a given current much greater than for the same magnet and armature, when they have been once subjected to the current. And to obtain a force nearly equal to that primarily produced it is necessary to reverse the current; but the maximum force exists only at the first closing of the circuit.

(*j*). The attraction of electro-magnets at a distance is weakened when from any cause the first closing of the circuit has not been followed by the complete attraction of the armature. This is due, as in the preceding case, to the effect of residual magnetism.

(*k*). The repellant force exerted by electro-magnets upon magnetized armatures is far from corresponding with the attractive force which is produced by reversing the poles of the magnet. This *fact*, which was observed in the early experiments upon electro-magnetism, and which was for a long time discussed by Mussembroeck and Abbe Nollet, is easily explained as an example of induction by the magnet, which tends to develop upon the armature a polarity opposite to that which exists in the magnet. Now, in attracting, the action of the induction is to increase the dynamic effect, while in repulsion it diminishes it. (*Etudes du Magnetisme*, p. 103.)

(*l*). When the iron core of an electro-magnet extends beyond the helix the force is diminished ; but if the poles be fitted with extension pieces in the inter-polar space, the force is augmented, and the maximum effect is reached when the space separating the auxilliary pieces is about one-fourth of the entire interval. This increase follows from the increase in the attractive surface of the poles, which then correspond to an armature.

(*m*). According to the experiments of M. Dub, the best condition of electro-magnets relating to the dimensions of their armatures are obtained when the different parts (separate branches, armature and bottom bar) are equal.

(*n*). This conclusion is naturally subordinate to conditions of application; for it is certain that if we desire prompt action in the armature, that it must be light; but we can then supply the deficiency of weight by reinforcing the poles of the magnet as above described.

3d. Conditions depending on the mass of the iron core.—The conditions of magnetic force depending on the diameter of the magnet and the degree of saturation may, under certain circumstances, be quite antagonistic; for though we gain force by increasing the diameter of the core, we may be subjected to loss because, by reason of size, the core is not charged to saturation, and then the central inert portion becomes, by a secondary action, like another armature. It has been attempted to obviate this difficulty by employing tubular magnets, which allow of easy magnetizing and demagnetizing; but it was found that there was a loss of force by this system, and which led to their rejection for a time. The author in 1862 began to study the conditions of force in this kind of magnet, and after many experiments presented a memoir to the *Académie des Sciences* containing the following conclusions:

(*a*). The greater force of electro-magnets with solid cores is not in consequence of their greater weight, but depends chiefly upon the disposition of their polar surfaces with reference to their armatures.

(*b*). If the polar extremity of a tubular magnet is furnished on the inside with a plug, which may be very thin, the force is very nearly the same as when the core is solid. But no such result is realized if the pole be augmented by a ring of iron outside the tube; which proves that it is not so much the increased amount of polar surface that reacts upon the attractive force as the disposition of this surface.

(*c*). If we consider in the case of the ring, that the latter acts as an armature, and that *such action* is prejudicial to the attractive force by disseminating it, as in the case of the magnet with several armatures; and that in the case of the plug or stopper there is a concentration of magnetic forces from different sides of the tube we can see why there should be a considerable difference of energy in the two cases; and we can readily estimate the result of the magnetic concentration in the second case if we suppose the plug projected upon the outside of the tube at the moment the latter is magnetized.

(*d*). It results from these effects that, to employ tubular electro-magnets with good effect, we ought to furnish their polar extremities with plugs whose thickness is at least equal to that of the tube. We may obtain an increase of force which in telegraphic magnets will be in the ratio of 25 to 38.

The thickness of the tube should bear proper relation to the strength of the current which excites the magnet. The experiments of Hughes upon telegraphic *instruments* led him to the conclusion that this thickness should be one-fourth the diameter. But the author's experiments led him to conclude that for electro-magnets of large size the thickness may be reduced below this proportion, and in a previous memoir the problem was treated at length,* where it was shown that

$$c' = c \sqrt[3]{\frac{x^3}{4(x-1)}},$$

in which c' represents the diameter of the tube; c the diameter of a solid iron core capable of saturation; x the divisor of c' to give the thickness. This value of x may without great inconvenience be made as high as 7.

(*e*). The inconvenience of solid magnets arises from residual magnetism and of magnetic condensation; but we can diminish considerably these effects by insulating magnetically the two branches from the bottom bar by copper discs, or by inserting in the bar itself a thickness of copper.

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* **Recherches sur les meilleures conditions de construction des *Electro*-Armants.**

IX.—RELATIONS WHICH THE GROUPING OF THE BATTERY BEAR TO THE CIRCUIT AND TO A GIVEN ELECTRO-MAGNET.

As it is a matter of importance that the electro-magnet should be properly adjusted to the current that charges it, it is, of course, equally important that the battery should be arranged with reference to producing the best effect upon a circuit containing a given magnet. Ohm has given a formula for such cases, which is found in all works on physics, but which is of limited application in practice—a fact which led the author in 1860 to seek for another method of analysis, based upon experimental grouping of the cells. The problem is to determine the most advantageous grouping of the elements of a battery to work against a known resistance. Thus, having a battery of 12 cells, it is required to know whether it will be best, in working against the resistance R, to arrange the cells in groups of 3 for quantity and 4 for tension, or in 6 groups of double elements, or 2 groups of sextuple elements, etc., etc.

Now, to determine the general formula, suppose the number of cells to be n. Let a be the number united for *tension* and b the number united for *quantity*. The expression for intensity of current, when r is the resistance in each cell and R the resistance of the circuit and E the electromotive force, is

$$I=\frac{E}{\frac{r}{b}+R}$$

for each group of b cups, and for the a groups united in tension

$$I'=\frac{aE}{\frac{ar}{b}+R} \text{ or } I'=\frac{abE}{ar+bR}.$$

Now, this formula, as well as that of Ohm, is susceptible of a maximum value, for as $ab=n$ and $b=\frac{n}{a}$ the equation becomes

$$I'=\frac{nE}{a+\frac{n}{a}R}=\frac{E}{\frac{ar}{n}+\frac{R}{a}}.$$

By considering a as the variable we find the maximum value corresponds to

$$\frac{r}{n}-\frac{R}{a^2}=0;\ \text{whence}\ a=\sqrt{\frac{nR}{r}},$$

$$\text{and as}\ a=\frac{n}{b},\ b=\sqrt{\frac{nr}{R}},\ \text{or simply}\ \frac{n}{a}.$$

This conclusion is easily reached without the aid of the differential calculus, as the author has previously shown in *Exposé des applicationes de l'Electricitie*, Vol. I.

Some important results are deduced from this condition of maximum value.

1st. When a battery is arranged for maximum value with reference to a given external resistance R; this resistance is equal to that of the battery, and from the equation

$$a=\sqrt{\frac{nR}{r}}\ \text{we get}\ R=\frac{a}{b}r,$$

and the right hand member of this equation represents the resistance of the battery.

2d. The most advantageous grouping of a battery for a given intensity, I, may be also determined, provided the resistance R is not greater than nr, as under maximum conditions we have

$$\frac{nE}{ar+bR}=\frac{nE}{2ar}=\frac{nE}{2br}$$

whence we get

$$a=\frac{2IR}{E} \text{ and } b=\frac{2Ir}{E};$$

very convenient and simple formulas for use in applications of electricity.

In some papers presented by the author to the *Académie des Sciences* in June and August, 1860, and in September, 1869, he indicated the limits of external resistance against which it is advantageous to employ certain specified methods of grouping of the battery. These limits for b cells joined for quantity are $\frac{nr}{(b-1)b}$ and $\frac{nr}{(b+1)b}$; that is to say, for cells in pairs the limits of resistance R, will be $\frac{nr}{2}$ and $\frac{nr}{6}$. For triple *grouping* the limits are $\frac{nr}{6}$ and $\frac{nr}{12}$. For

ple $\frac{nr}{12}$ and $\frac{nr}{20}$, etc., etc.; and
so been shown that, as Oh
oved that the resistances R co
ling to maxium effects for di
rrangements of the battery, a
nted by $\frac{nr}{b^2}$; that is to say by
bled cells, $\frac{nr}{9}$ for tripled, $\frac{nr}{16}$ f
pled, etc., etc. Finally it w
trated that the limits of resis
the external circuit for which th

Thus we know by the preceding calculation that for a Daniell battery of 20 cells the resistances of the external circuit, which would require an arrangement of the cells in pairs, lie between 10,000 meters and 3333 meters of telegraph wire. If the resistances are between 3333^{m} and 1666^{m}, the cells may be in threes, and if between 1666^{m} and 1000^{m} we may adopt the quadruple arrangement.

It is seen from the foregoing that there is no difficulty in determining the best arrangement of any given number of cells to work against any given resistance, since it will suffice to divide the total

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cells joined for quantity in two consecutive groupings, we find in equating the two expressions:

$$ar+bR=a'r+b'R$$

or

$$R(b-b')=r\left(\frac{n}{b}-\frac{n}{b'}\right)$$

whence

$$R=\frac{nr}{bb'}.$$

This may be transformed into

$$=R\frac{nr}{(b-1)b} \text{ or } R=\frac{nr}{(b+1)b}$$

according as we compare the groupings. But if we make $b=b'$ then $R=\frac{nr}{b^2}$ and we arrive at the *maximum values* previously obtained.

resistance of the n cells successively b 4, 9, 16, etc., and see which quotien most nearly corresponds to the externa resistance. The divisor then represents the square of the number of cells in each group, and the number of groups is obtained by dividing n by the number o cells thus grouped for quantity.

All these calculations are exceedingly simple, and it seems astonishing that so much time and money is expended in useless researches and trials, when the best conditions for useful effect are so easily determined.

Some exacting people assert that these calculations are only rigorously true when we get whole numbers for results, as we cannot divide a battery cell; but in electrical applications we are satisfied with approximate results. It is true we cannot divide the cell of a battery, and so we cannot always realize the maximum conditions; but the calculation affords us a means of determining what numbers to adopt in grouping to obtain the best *result*. Thus in the example in Chapter

V. we found the value of $a = 3.074$; now it is evident that 3 groups in intensity are indicated, and as 8 divided by 3 gives 2.7, there should be 3 cells in each row.

The formulas presented in the preceding articles enable us to compare the forces of different electric generators. There are, however, in these calculations certain considerations which, not having been viewed in the same light by different physicists, have led to disagreements that are to be regretted. Thus, according to Jacobi, we may compare two batteries, both of which are working under maximum conditions; but for this purpose the exterior and interior resistances for each case must be equal. The intensity of each would then be $\frac{nE}{2ra}$ or $\frac{nE}{2bR}$. Now if for the battery taken as the standard of comparison, we assume $n=1$, which reduces the preceding formula to $\frac{E}{2r}$; we have if we assume the intensities equal:

$$\frac{nE}{2ar}=\frac{E'}{2r'} \text{ and } \frac{nE}{2br}=\frac{E'}{2r'};$$

equations which may be put under the form,

$$\frac{bE}{2r}=\frac{E'}{2r'}, \text{ and } \frac{aE}{2R}=\frac{E'}{2r'},$$

and we can deduce the values of a and b by supposing the resistance R to the resistance r' of the cell of comparison. Then we have

$$a=\frac{E'}{E} \text{ and } b=\frac{E'}{E}\times\frac{r}{r'}$$

and the total number of elements is found by multiplying a by b.

Proceeding on this plan, we find that 5 Bunsen cells represent 9 Daniell cells, each with a surface 11 times as great; which indicates that we should employ 20 Daniell cells, conveniently arranged, as an equivalent for one Bunsen cell. It has been similarly found that 3 Bunsen cells equal in intensity 4 cells of the mercury sulphate battery, each of which had a surface three and a third times that of the Bunsen cell; which indicates that it would require 5 of the mercury sulphate cells to be equal to one Bunsen.

When this method of Jacobi has been duly considered, it is seen that he desired to avoid giving the exterior resistance R a determinate value; but in fact this resistance is represented in the resistance of the battery which is employed as a unit of comparison, and in the preceding example it is equal to 153 meters of telegraph wire. Now, it is easy to see that in proportion as the resistance increases or diminishes, the above figures are singularly modified; for the value of R may be reduced more or less or become more or less preponderant in the value of the denominator of the expression for intensity of current. It is this fact which excites the criticisms of many physicists, We could perhaps take for a starting point a value of R which would be a mean of the resistance of the different cells, but we should not have gained much, and this system of comparison would apply only to short circuits. In such a case we might begin by taking I equal to the intensity of the battery chosen as a standard of comparison, and than obtain the values a and b by the formulas $a=\frac{2\mathrm{IR}}{\mathrm{E}}$ and $b=\frac{2\mathrm{I}r}{\mathrm{E}}$, which in the case of the Bunsen and Daniell batteries will give for a resistance

$$\mathrm{R}=153^{\mathrm{m}},\ \mathrm{I}=36.55.$$

$$a=\frac{2\times 36.55\times 153}{5973}=1.87,$$

and
$$b=\frac{2\times 36.55\times 931}{5973}=11.4.$$

This brings us back to the conclusion previously reached, as R is the resistance of the battery used as a standard of comparison. Suppose $\mathrm{R} = 1000^{\mathrm{m}}$, then I becomes equal to 9.64, $a = 3.2$, and $b = 3$, and we see that instead of employing 20 Daniell cells it will be necessary to use only 9 to obtain the equivalent of a Bunsen cell.

X.—TABLES FOR USE IN CALCULATIONS RELATING TO ELECTRO-MAGNETS.

The following tables are believed to be indispensable to a work treating of calculations in electro-magnetism. It should be mentioned that by reason of the omission in Ohm's formula, of a term dependent on polarization effects, the figures representing the resistances of battery cells are too large, and as they increase with the resistances of the external circuit,* there are given in the first table values both for short circuits and for resistent circuits.

The first values were calculated by M. Ed. Becquerel; the second by the author; so that to obtain the best results it will be necessary to use the author's figures when the external resistances are great and Becquerel's when they are small.

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* In taking into account the effect of polarization, the formulas for E and r according to Ohm's method are:

$$E=\frac{II'(R'-R)+(Ie'-I'e)}{I-I'} \text{ and } r=\frac{(I'R'-IR)-(e-e')}{I-I'}$$

which differ from the applied formulas only in the second terms of the numerators, which do not appear in the latter. This omission causes the calculated *values to be greater* than the quantities R and R'.

TABLE NO I.—VOLTAIC CONSTANTS.

Batteries in common use.	Electromotive force E.	Resistance r in meters		Ratio of electromotive force.
		Du Moncel.	Becquerel.	
Daniell battery (French telegraph pattern)....	5973	931	180	1.00
Bunsen's cell (amalgamated zinc)..........	11123	153	57	1.86
Delaurier cell (chromic acid and salt solution)	12413	366	"	2.08
Chutaux cell (potassic bichromate)..........	11400	600	"	1.91
Duchemin cell (ferric chloride and salt solution).................	9640	942	"	1 61
Marie Davy cell (mercuric sulphate and water)...............	8192	550	"	1.37
Leclanché cell (large size).................	7529	400	"	1.26
De la Rues cell (fused silver chloride and zinc chloride; size, minute)...........	5596	748	"	0.94
Prudhomme's cell (lead sulphate and water...	3301	880	225	0.55

TABLE No. II.—DIMENSIONS OF WIRE USED FOR ELECTRO-MAGNETS.

	Gauge numbers.	Diam. naked wire.	Diam. covered wire.	Values of f.	f^2.
		m.	m.		
Common gauge, silk covered.	No. 32	0.00014	0.00023	1.6428	2.6988
	" 28	0.00022	0.00033	1.5000	2.2500
	" 24	0.00027	0.00040	1.4814	2.1934
	" 20	0.00035	0.00048	1.3714	1.8796
	" 16	0.00040	0.00055	1.3750	1.8906
	" 12	0.00049	0.00065	1.3265	1.7582
	" P	0.00058	0.00077	1.3275	1.7609
Decimal gauge, cotton covered.	No. 1	0.00060	0.00122	2.0333	4.1331
	" 2	0.00070	0.00134	1.9143	3.6634
	" 3	0.00080	0.00146	1.8250	3.3306
	" 4	0.00090	0.00158	1.7555	3.0800
	" 5	0.00100	0.00172	1.7200	2.9584
	" 6	0.00110	0.00184	1.6727	2.7989
	" 7	0.00120	0.00196	1.6333	2.6687
	" 8	0.00130	0.00208	1.6000	2.5600
	" 9	0.00140	0.00220	1.5714	2.4670
	" 10	0.00150	0.00232	1.5466	2.3901
	" 11	0.00170	0.00254	1.4941	2.2320
	" 12	0.00180	0.00266	1.4777	2.1844
	" 13	0.00200	0.00288	1.4444	2.0851
	" 14	0.00210	0.00300	1.4285	2.0392
	" 15	0.00235	0.00327	1.3915	1.9349
	" 16	0.00260	0.00354	1.3615	1.8523

The figures in Table No. 2, giving the values of the diameters of wire, with and without the silk covering, are not exactly the results obtained by direct measurement. These results are deduced from measurements with the rheostat upon manufactured electro-magnets, so that open spaces and other irregularities of winding are taken into account. This method is not very exact in one sense, but it is clear that it gives values much more serviceable for calculation, for it takes into account quantities which would otherwise be neglected.

These values are easily calculated from formula (5). When $a = 0.012$, $e = 0.012$ and $b = 0.12$

$$g^2 = f\sqrt{\frac{0.0000000000289529}{H}}$$

and as $\frac{g}{f} = s$, s representing the diameter of the copper wire, measured directly without the silk,

$$f = \sqrt{\frac{0.000000000028952}{\substack{H \\ s^2}}}$$

TABLE No. III.—DIMENSIONS OF WIRE IN COMMON USE.

Old Gauge	Diameter uncovered.	Meters per kilogram.	Diameter covered wire.	Meters per kilogram.	Resistance per kilogram.
No.	m	m	m		
12	0.00056	514	0.00054	515	—
14	0.00050	680	0.00048	673	—
16	0.00044	796	0.00044	780	22.30
18	0.00040	867	0.00040	929	29.60
20	0.00036	1238	0.00034	1390	31.47
22	0.00032	1439	0.00032	1420	—
24	0.00028	1925	0.00028	1872	43.75
26	0.00026	2389	0.00026	2257	138.23
28	0.00024	2854	0.00022	3230	174 94
29	0.00023	3054	0. —	—	185.77
30	0.00021	3822	0.00020	3920	228.46
31	0.00020	4042	0.00019	4390	471.51
32	0.000185	5875	0.00017	4810	528.57
33	0.00017	6130	0 00015	9400	967.56
34	0.00016	7750	0.00 14	9580	—
38	0 000125	10550	0.000125	9650	1680
39	0 000115	11950	0.000115	10600	—
40	0.00010	18400	0.00009	16290	—
42	0.00008	24800	—	—	4228
43	0.000075	25600	0.00007	26310	
44	0.00006	36500	0.00006	35400	17

Table No. IV.—Dimensions of Wire I Common Use.

Decimal Gauge.	Meters per kilogram.	Diameters.
No.		
P	670	0.0005
1	418	0.0006
2	330	0.0007
3	208	0.0008
4	180	0.0009
5	160	0.0010
6	137	0.0011
7	100	0.0012
8	85	0.0013
9	75	0.0014
10	70	0.0015
11	66	0.0016
12	54	0.0018
13	40	0.0020
14	34	0.0022
15	30	0.0024
16	26	0.0027
17	19	0.0030
18	16	0.0034
20	10	0.0044

Tables 3 and 4 have been prepared with much care by M. Bonis, a manufacturer of wire in Paris, who uses copper whose conductivity is 94 to 96.

The covered wire is smaller than the wire before covering, because of the tension to which they are subjected in the covering process, which causes a reduction in diameter averaging three hundredths of a millimeter. So that there is an increased length per kilogram for some of the sizes.

In the preceding tables the resistances are given in meters of telegraph wire. These are reduced to *ohms* by dividing by 100.

The values of electromotive force in Table 1 may be reduced to *volts* by multiplying by 1.079.

Di milli		kilogram.	kilogram.
	Old gauge.		
0.02	—	355584	1803084
0.10	40	14369	30377
0.20	31	3614	1922
0.30	23	1607	378
0.40	18	902	119
	Decimal gauge.		
0.50	14	576	49
0.60	1	401	24
0.70	2	294	13
0.80	3	226	7.5
0.90	4	178	4.6
1.00	5	144	3.0
1.50	10	64	0.59
2.00	13	36	0 19

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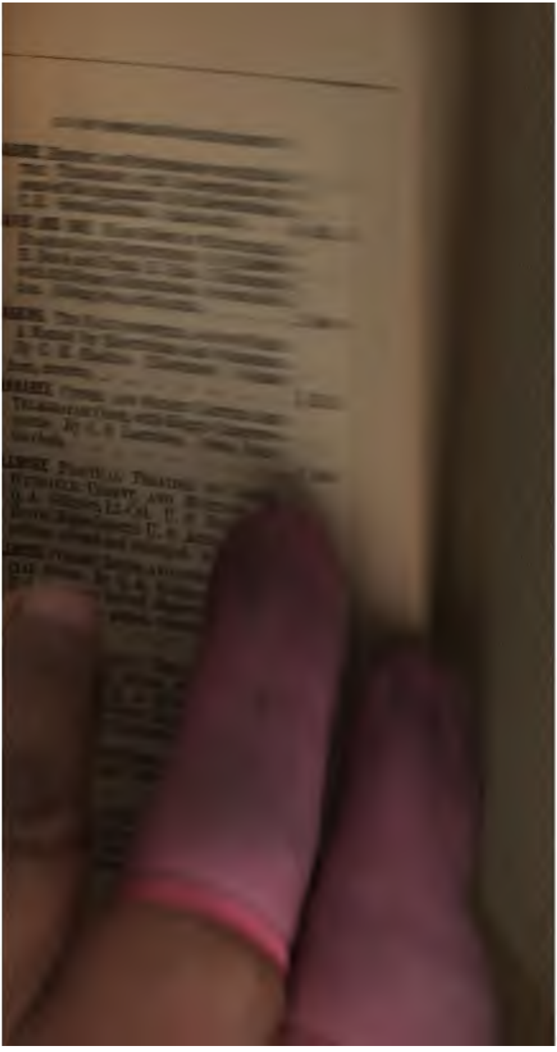

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